Influence of Surface and Bottom Stress in the Coupled Ocean Circulation and Wind-Wave Models

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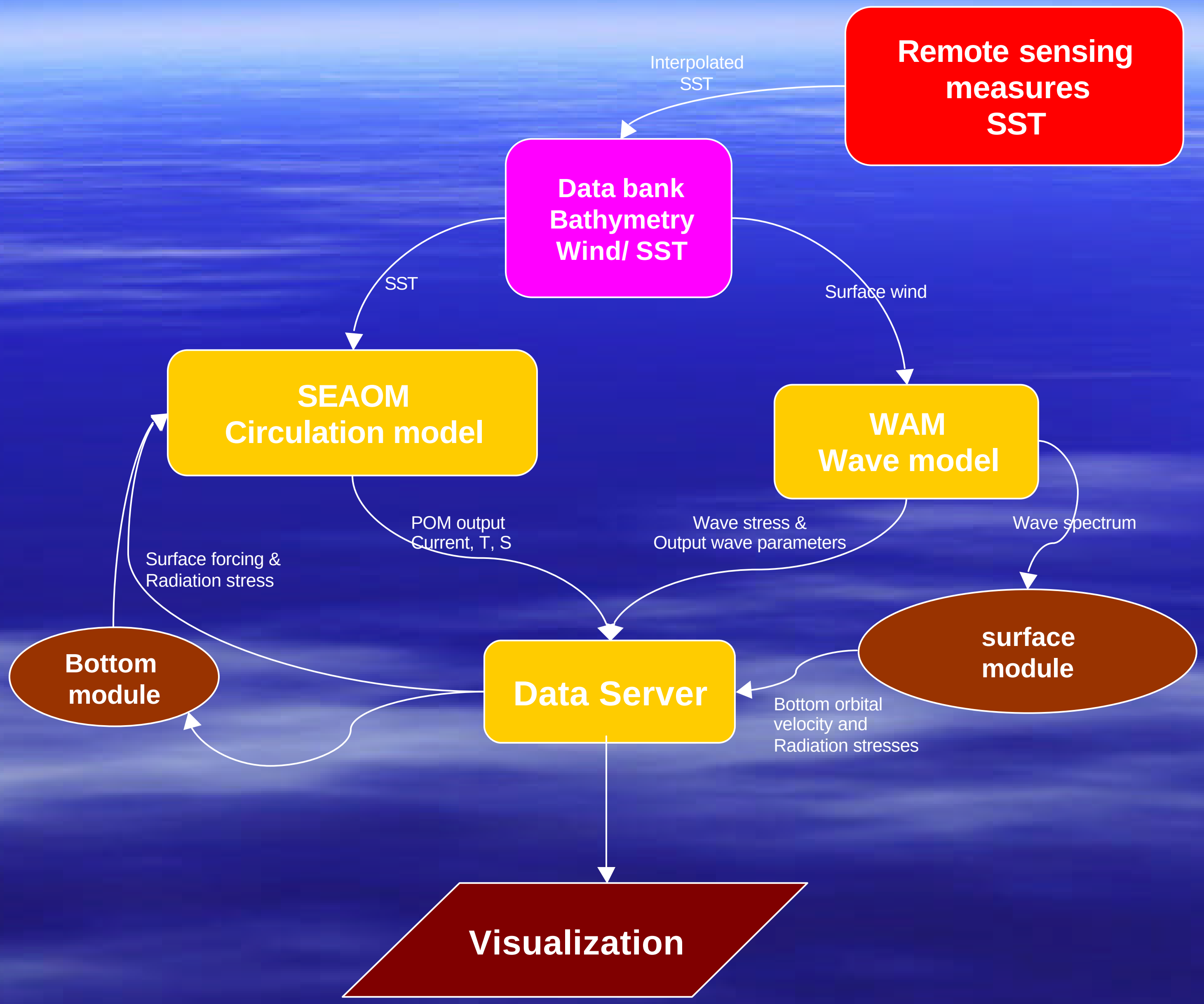
COUPLED CIRCULATION & WAVE MODEL



Outlines

- Wind-wave modeling
- Circulation modeling
- Coupling of ocean models
- Influence of Wind Waves on Surface and Bottom Stress
- Research Domain:

  9^oS - 24^oN

  99^oE - 121^oE

South East Asian Ocean Model
(SEAOM) – POM based

- High resolution of 1/6 x 1/6 degree.
- Sigma coordinate in the vertical coordinate.
- Imbedded turbulence closure sub-model to provide vertical mixing coefficients.
- A free surface and a split time step.
- Complete thermodynamics have been implemented.

3-D Hydrodynamics Model

- **The continuity equation**

$$\nabla \cdot U + \frac{\partial w}{\partial z} = 0$$

- **The Reynolds momentum equations.**

$$\frac{\partial u}{\partial t} + V \cdot \nabla u + w\frac{\partial u}{\partial z} - fv = -\frac{\partial}{\partial \rho_0}\frac{\partial P}{\partial x} + \frac{\partial}{\partial z}\left(K_M \frac{\partial u}{\partial z}\right) + F_x$$

$$\frac{\partial v}{\partial t} + V \cdot \nabla v + w\frac{\partial v}{\partial z} + fu = -\frac{\partial}{\partial \rho_0}\frac{\partial P}{\partial y} + \frac{\partial}{\partial z}\left(K_M \frac{\partial v}{\partial z}\right) + F_y$$

$$F_x = \frac{\partial}{\partial x}\left[2A_M \frac{\partial u}{\partial x}\right] + \frac{\partial}{\partial y}\left[2A_M\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)\right]$$

$$F_y = \frac{\partial}{\partial y}\left[2A_M \frac{\partial v}{\partial y}\right] + \frac{\partial}{\partial x}\left[2A_M\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)\right]$$

- **The turbulent kinetic energy equations.**

$$\frac{\partial q^2}{\partial t} + V \cdot \nabla q^2 + w\frac{\partial q^2}{\partial z} = \frac{\partial}{\partial z}\left(K_q \frac{\partial q^2}{\partial z}\right) + 2K_m\left[\left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2\right] + \frac{2g}{\rho_0}K_H\frac{\partial \rho}{\partial z} - \frac{2q^3}{B_1 l} + F_q$$

$$\frac{\partial (q^2 l)}{\partial t} + V \cdot \nabla (q^2 l) + w\frac{\partial (q^2 l)}{\partial z} = \frac{\partial}{\partial z}\left(K_q \frac{\partial (q^2 l)}{\partial z}\right) + E_1 l\left\{K_m\left[\left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2\right] + E_3\frac{g}{\rho_0}K_H\frac{\partial \rho}{\partial z}\right\} - \frac{q^3}{B_1}\tilde{W} + F_l$$

SEAOM – Boundary Conditions

Input

- Surface Forcing
  - Surface stress
  - Heat flux/SST
- Bottom Conditions
  - Bathymetry
  - Wave-current interaction
- Lateral Conditions
  - Temperature
  - Salinity
  - Elevation
  - Flow rate

Output

- Current
- Temperature
- Salinity
- Density
- Diffusion coefficient
- elevation

WAM : A Third Generation Ocean Wave Prediction Model (cycle 4)

WAMDI group (1988)
Komen et al. (1994)
Gunther et al. (1992)

Evolution of the two-dimensional wave spectrum, F(f, θ,t) in spherical coordinates, is governed by the transport equation

$$\frac{\partial F}{\partial t} + (\cos\phi)^{-1}\frac{\partial}{\partial \phi}\left(\dot{\phi}\cos\phi\, F\right) + \frac{\partial}{\partial \lambda}\left(\dot{\lambda} F\right) + \frac{\partial}{\partial \theta}\left(\dot{\theta} F\right) = S$$

where ϕ is latitude; λ is longitude

- Spectral energy balance concept
- Featuring nonlinear quadraplet wave-wave interaction
- Solves wave transport equation
- Cycle 4: New wind input physics
- A third generation wave model

Wind forcing

$S_{dis} = S_{wc} + S_{dibr} + S_{bot} + S_{vis}$

$$S = S_{in} + S_{dis} + S_{nl}$$

Nonlinear energy transfer

WAM : A Third Generation Ocean Wave Prediction Model (cycle 4)

Functionality and output of the model

- Cartesian or spherical propagation
- Deep and shallow water
- Without or with depth and current refraction
- Dissipation of white-capping
- Wave generation by wind
- Nonlinear wave-wave interaction

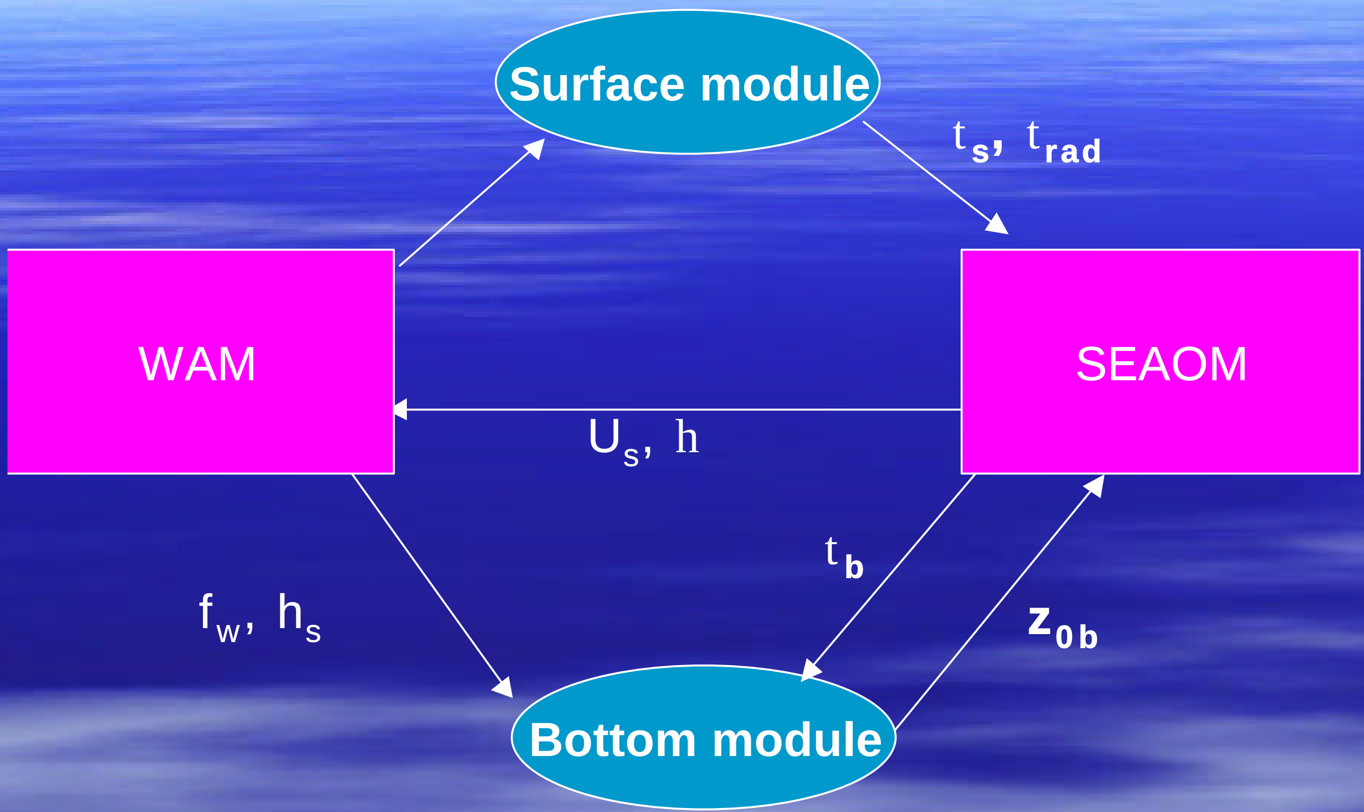
Inputs

- Wind source,
- Bathymetry
- Current data

Outcome

- Significant wave height;
- Mean wave direction
- Mean frequency
- Friction velocity
- Wind direction
- Wave peak frequency
- Drag coefficient
- Normalized wave stress
- Two-dimensional spectra

Coupling Modes



f_w = peak wave frequency
t_b = bottom shear stress
U_s = surface current
t_s = surface shear stress
t_{rad} = radiative shear stress
h_s = wave height
h = sea level
z_{0b}=bottom roughness

Wind Stress

Surface stress due to wind:

$$t = r_a C_D U_{10}^2$$

$$C_D = \begin{cases} 1.14 \times 10^{-3} & U_{10} < 10\ m/s \\ (1.14 + 0.065\,U_{10}) \times 10^{-3} & U_{10} > 10\ m/s \end{cases}$$

ρ_a – air density

C_D – drag coefficient

U_{10} – wind speed at 10m height

Surface Stress

Wave-induced Stress:

$$t_w = r_w \int w \, g \; (F \bullet \cos \; (q \; - j \;) df \;\; d q$$

Surface roughness:

$$z_{0s} = \frac{a t}{r_a \, g \sqrt{1 - t_w / t}}$$

Drag coefficient:

$$C_D = \left[\frac{k}{\ln(10 / z_{0s})} \right]^2$$

Surface stress over sea wave:

$$t = r_a C_D U_{10}^2$$

θ – Wave propagation direction

φ – wind direction

ω – angular frequency

γ – growth rate of wave

F – 2-D spectrum

ρ_w – water density

α– Charnock constant

κ– Von Karman constant

Conceptual Bottom Boundary

- **Conceptual bottom friction factor**

$$t_b = r\, \boldsymbol{C}_{z_r} \,|\vec{\boldsymbol{U}}_r|\, \boldsymbol{U}_r$$

- **Bottom drag coefficient**

$$C_{z_r} = \left[k \;/\; ln \frac{z_r}{z_0} \right]^2$$

z_r is close enough to the bottom to be considered within the constant stress layer

U_r=U(z_r), the reference velocity

z_0 is equated to the bottom roughness

Bottom Roughness

- The Shields Parameter *[Madsen,1993]*,

$$PSIPR = \Psi'_m = \frac{U'^{2}_{*wm}}{(s-1)gd}$$

where

$$U'^{2}_{*wm} = \frac{1}{2} f'_w U_{bm}^{2}$$

$$f'_w = \exp\left\{ 5.61 \left(\frac{U_{bm}}{d\,\omega_r} \right)^{-0.109} - 7.30 \right\}$$

d	*sediment diameter*
s	*relative density of sediment to water*
U_{bm}	*wave near bottom orbital velocity amplitude*
ω_r	*periodic wave radian frequency*
F_w'	*wave friction factor*
U_{*wm}'	*maximum friction velocity due to wave*

No sediment motion	$\Psi'_m < 0.03,$	$k_N = d$
Rippled flow	$0.03 < \Psi'_m < 0.35,$	$k_N = 0.83 \dfrac{U_{bm}}{\omega_r}$
Flat with sheet flow	$\Psi'_m > 0.35,$	$k_N = 15\,\Psi'_m d$

k_n the equivalent Nikuradse sand grain roughne

Wave Parameters

Near bottom velocity directional spectrum :

$$S_{U_bU_b}(w,f) = \left(\frac{w}{\sinh kD}\right)^2 S_{hh}(w,f),$$

Bottom orbital velocity amplitude:

$$U_{bm} = \left[2\iint S_{U_bU_b}(w,f)\,dw\,df\right]^{\frac{1}{2}}$$

Wave radian frequency:

$$w_r = \frac{\iint w\, S_{U_bU_b}(w,f)\,dw\,df}{\iint S_{U_bU_b}(w,f)\,dw\,df}$$

Dominant direction:

$$\tan f_w = \frac{\iint \sin f\; S_{U_bU_b}(w,f)\,dw\,df}{\iint \cos f\; S_{U_bU_b}(w,f)\,dw\,df}$$

Wave Parameters

Near bottom velocity directional spectrum :

$$S_{U_bU_b}(\omega,\phi) = \left(\frac{\omega}{\sinh kD}\right)^2 S_{\eta\eta}(\omega,\phi),$$

Bottom orbital velocity amplitude:

$$U_{bm} = \left[2\iint S_{U_bU_b}(\omega,\phi)\,d\omega\,d\phi\right]^{\frac{1}{2}}$$

Wave radian frequency:

$$\omega_r = \frac{\iint \omega\, S_{U_bU_b}(\omega,\phi)\,d\omega\,d\phi}{\iint S_{U_bU_b}(\omega,\phi)\,d\omega\,d\phi}$$

Dominant direction:

$$\tan\phi_w = \frac{\iint \sin\phi\, S_{U_bU_b}(\omega,\phi)\,d\omega\,d\phi}{\iint \cos\phi\, S_{U_bU_b}(\omega,\phi)\,d\omega\,d\phi}$$

Wave-Current Interaction

angle between wave and current:

$$\phi_{wc} = \phi_c - \phi_w.$$

wave bottom shear stress :

$$\tau_{wm} = \frac{1}{2}\rho_w f_w U_{bm}^2$$

wave friction factor:

$$f_w = \exp\left\{7.02\left(\frac{U_{bm}}{k_n\omega_r}\right)^{-0.078} - 8.82\right\}.$$

relative strength factors of currents and waves:

$$\mu = \frac{\tau_c}{\tau_{wm}}$$

$$C_\mu = \left\{1 + 2\mu\left|\cos\phi_{wc}\right| + \mu^2\right\}^{\frac{1}{2}}.$$

combined wave-current friction factor:

$$f_{wc} = C_\mu \exp\left\{7.02\left(\frac{C_\mu U_{bm}}{k_n\omega_r}\right)^{-0.078} - 8.82\right\},$$

wave bottom shear stress in the presence of a current:

$$\tau_{wm} = \frac{1}{2}\rho_w f_{wc} u_{bm}^2$$

Wave-Current Interaction - continued

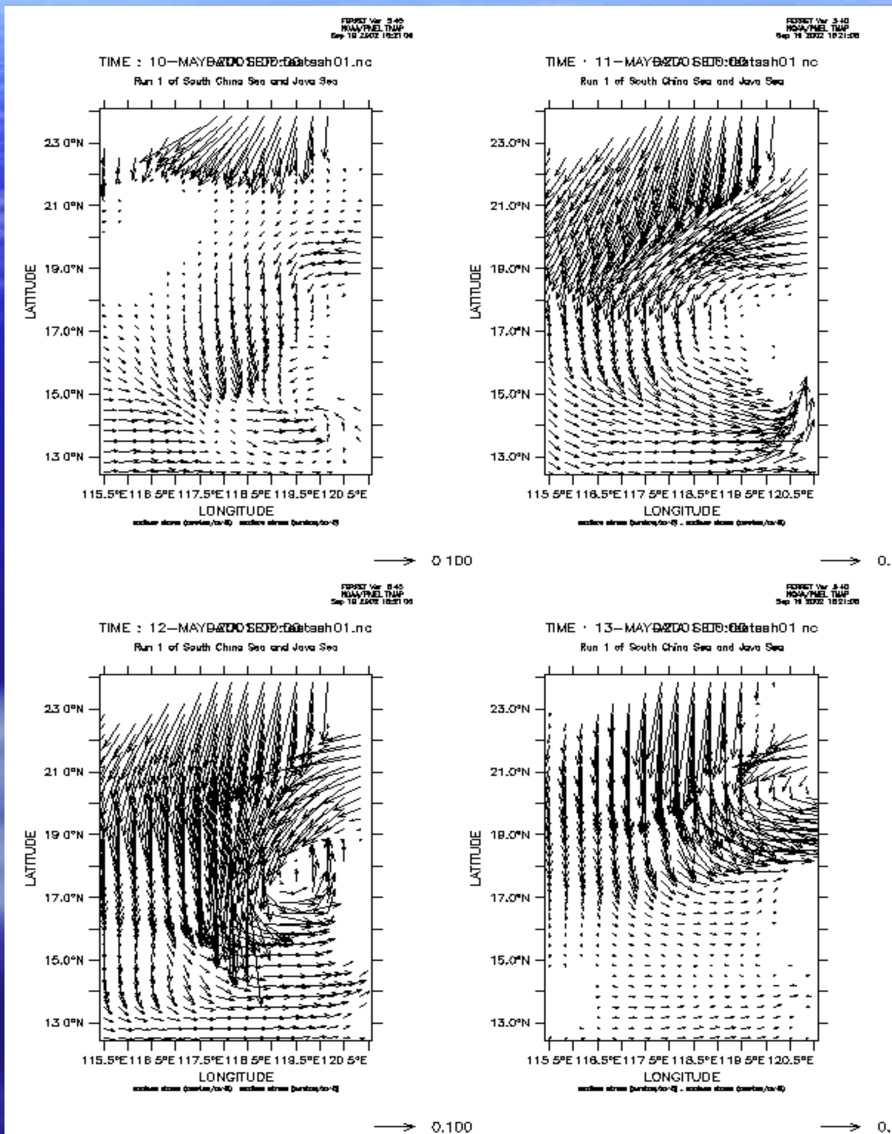
wave boundary layer thickness:

$$\delta_{wc} = A\kappa \frac{\sqrt{\dfrac{C_\mu \tau_{wm}}{\rho_w}}}{\omega_r}$$

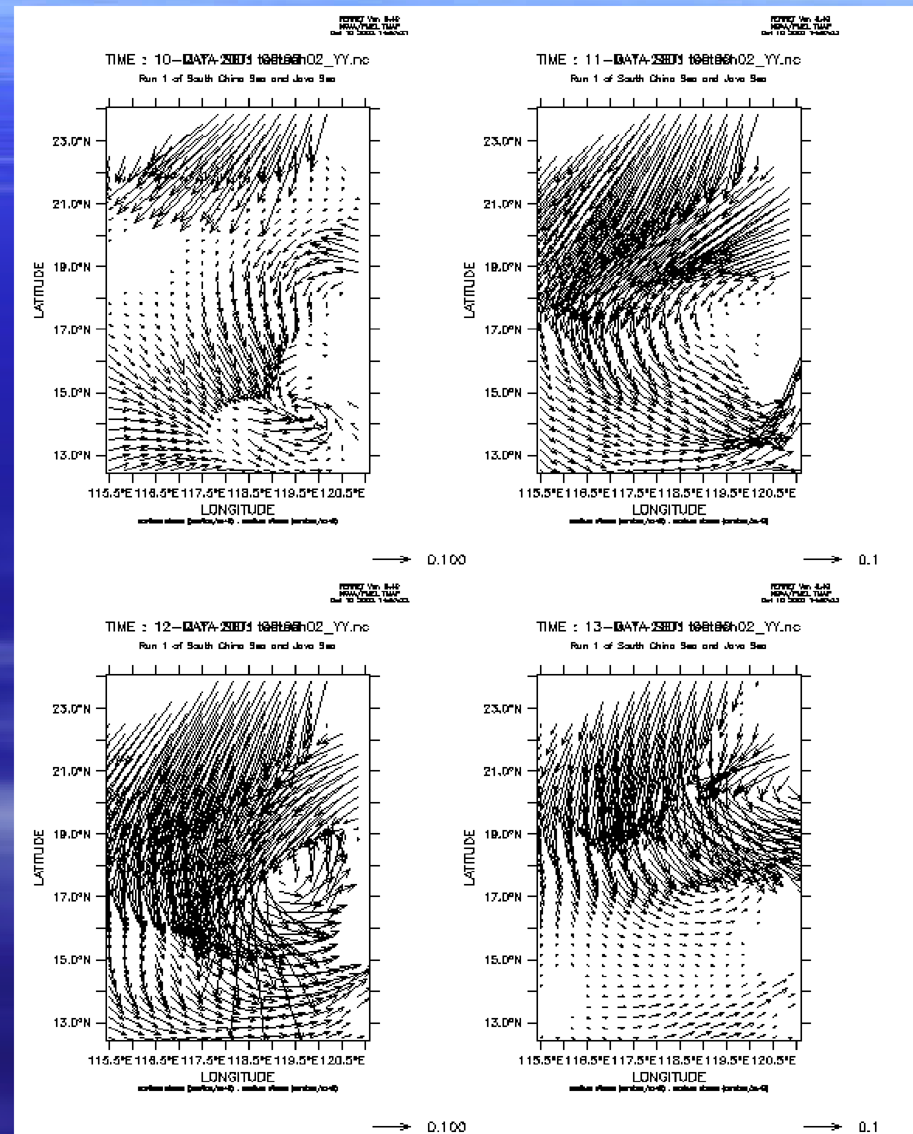
apparent roughness:

$$Z_0 = \delta_{wc} \left[\frac{30\,\delta_{wc}}{k_N} \right]^{-\sqrt{\dfrac{\tau_c}{C_\mu \tau_{wm}}}}$$

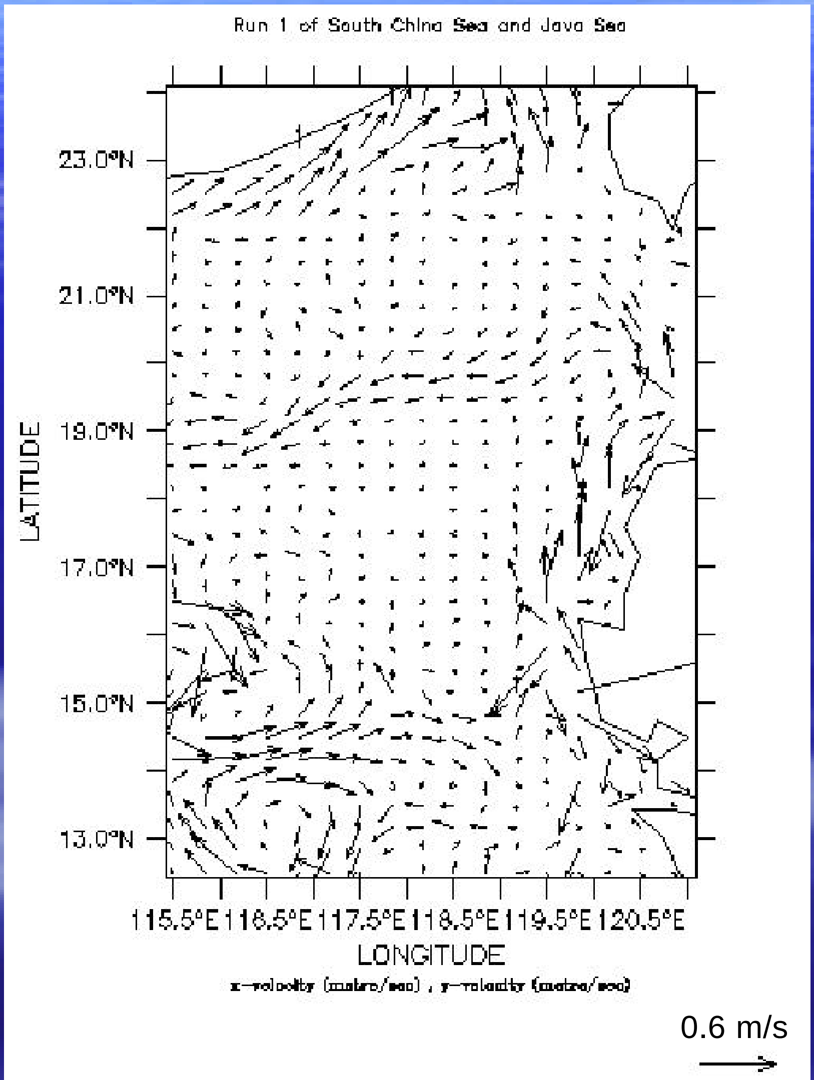
Wind Stress at Surface

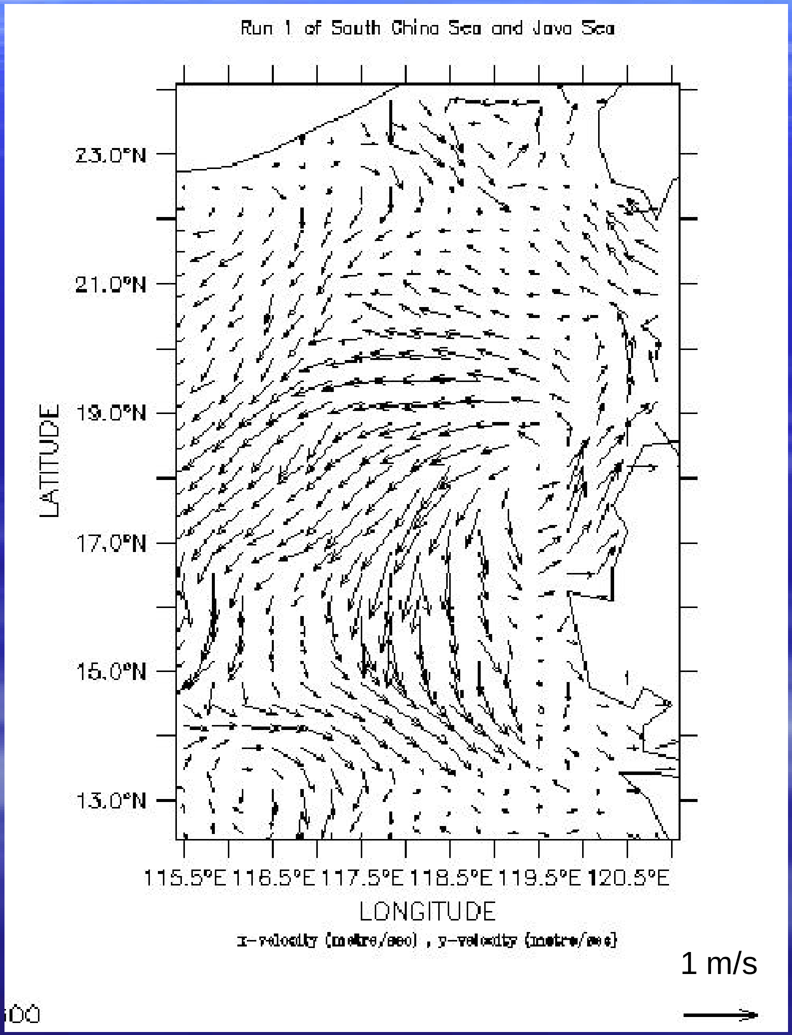


Surface Stress over sea wave



No surface & No Bottom wave effects





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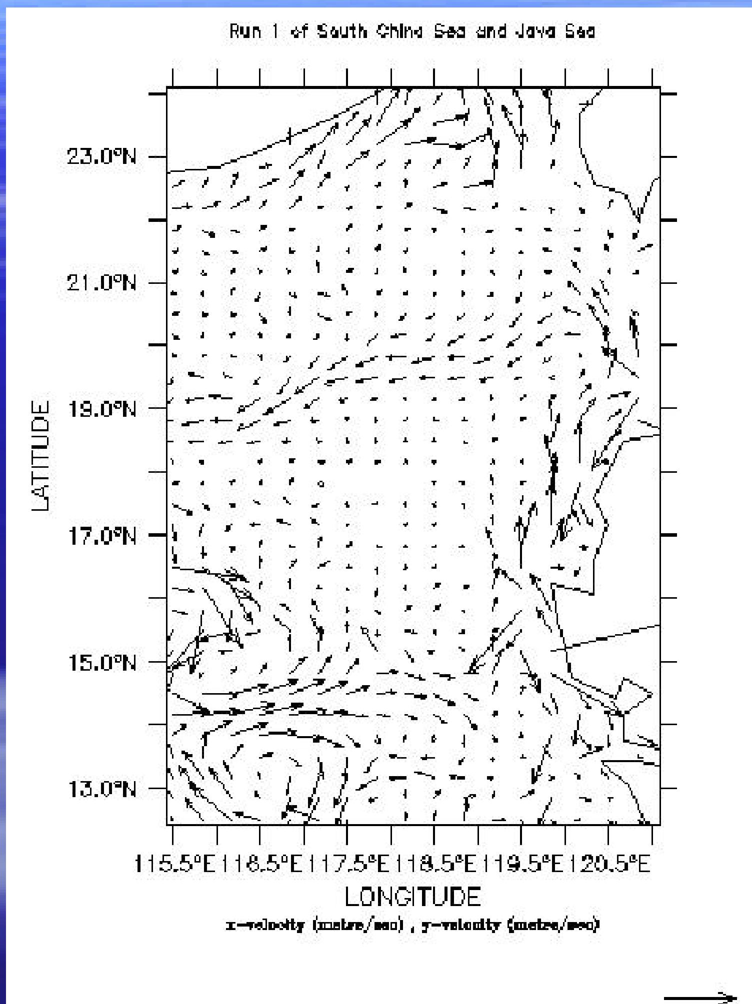
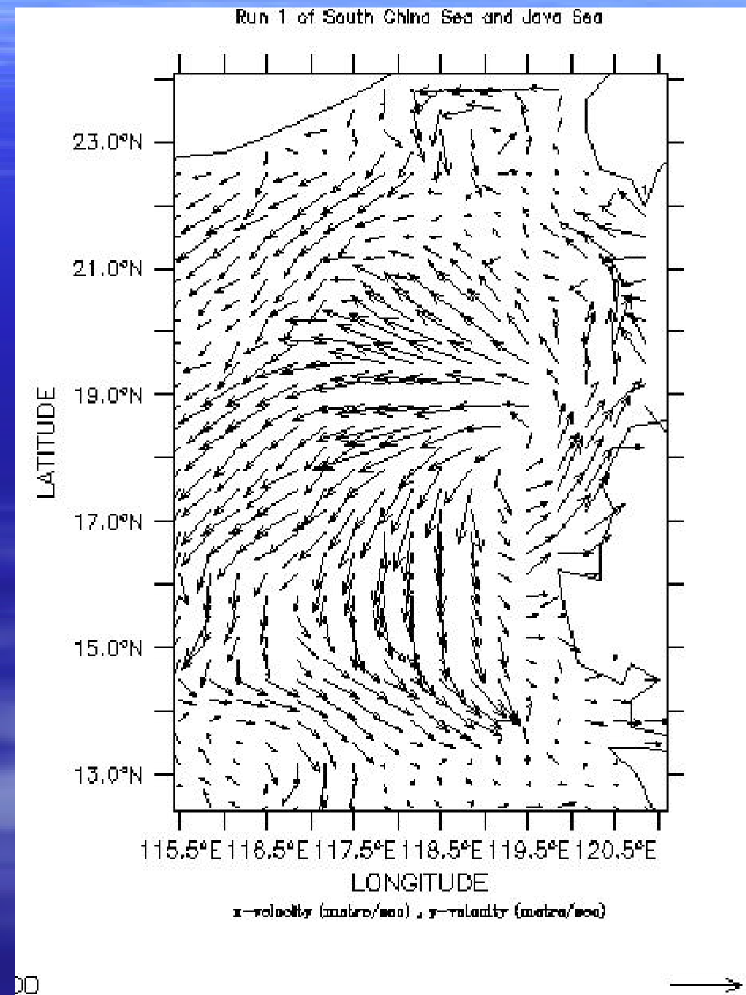
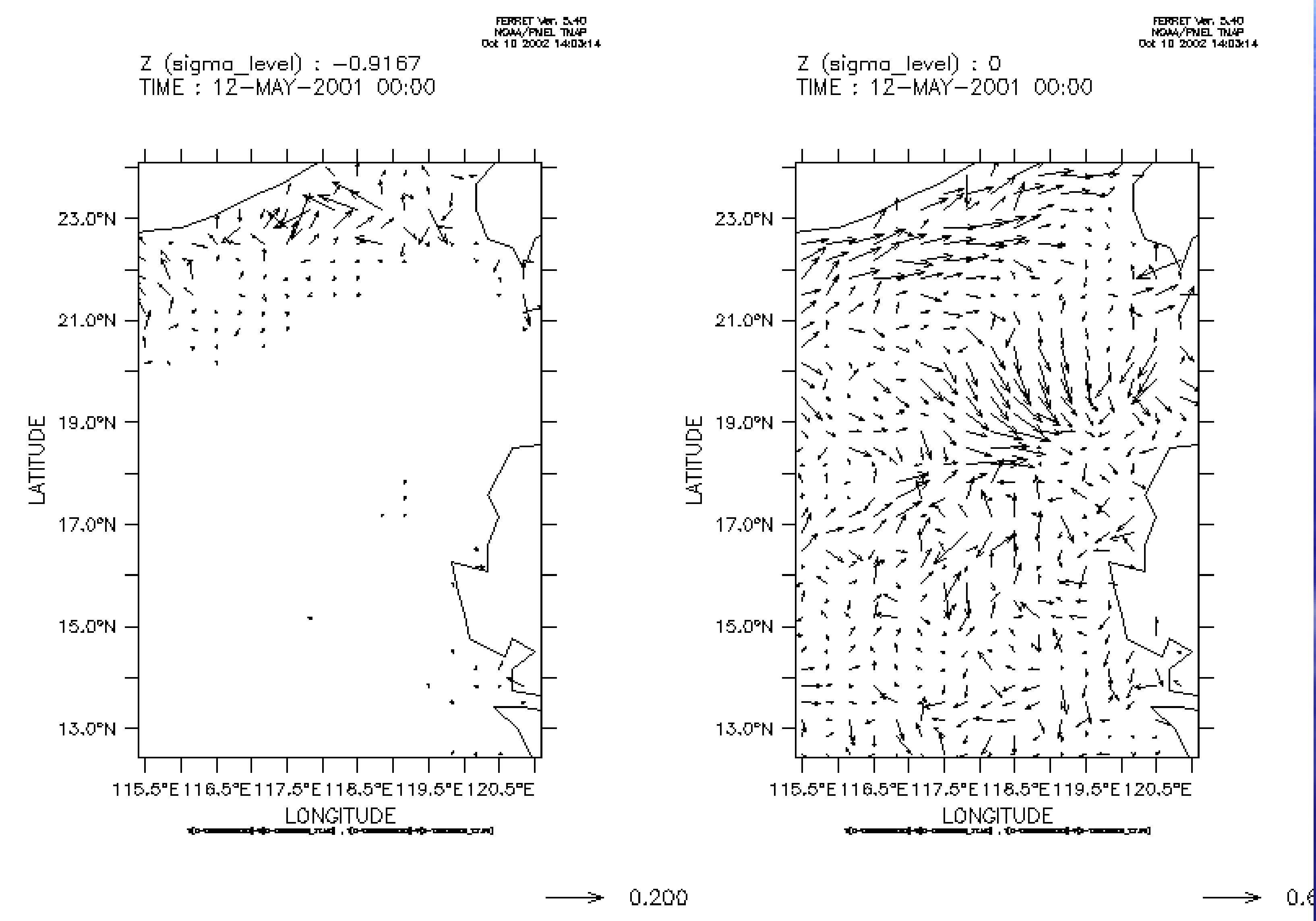
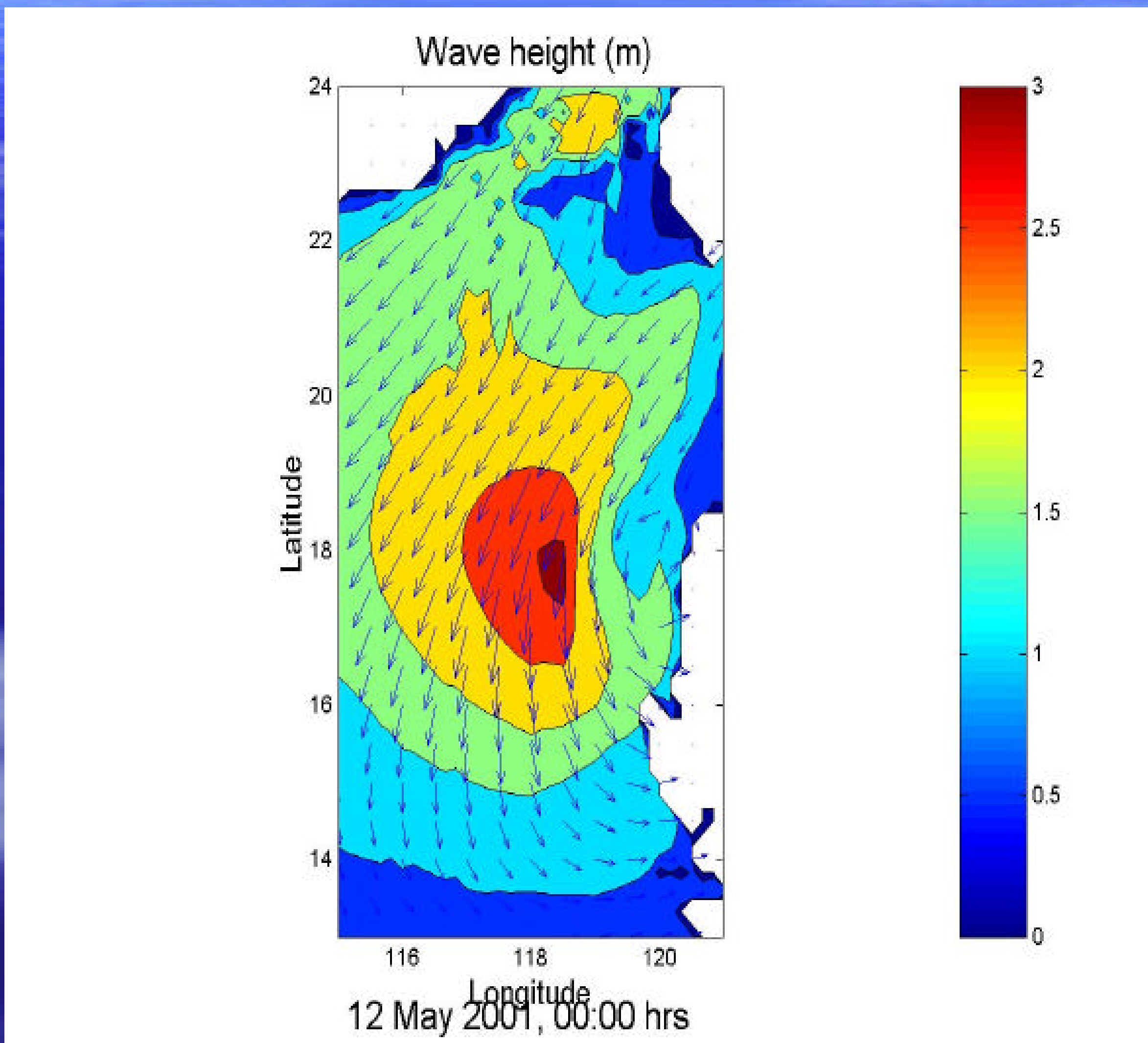




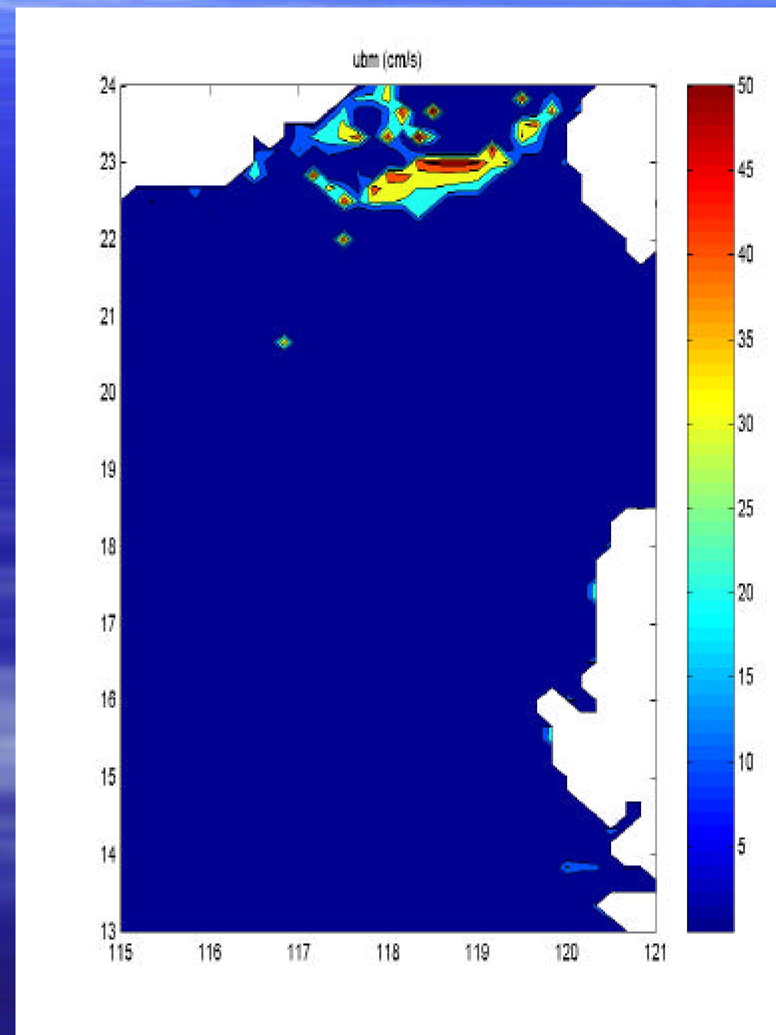
Difference for wave induced surface stress



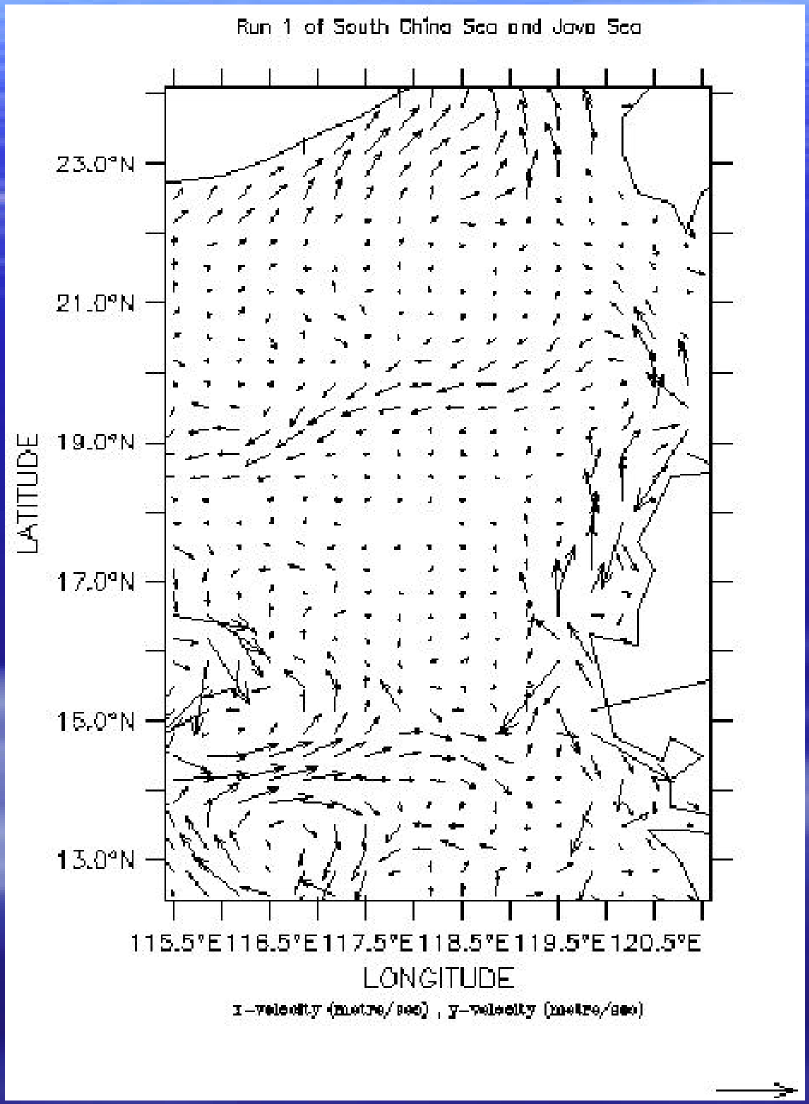
Wave Height
on May 12, 2001

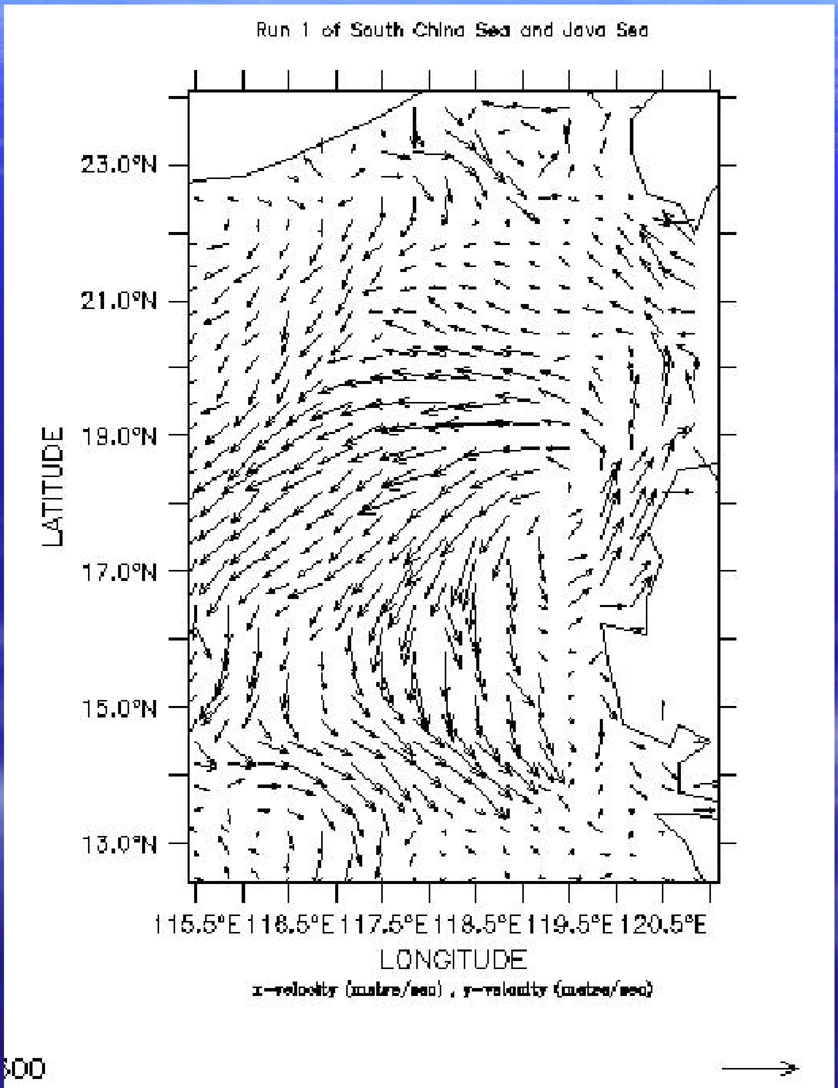


Bottom Orbital velocity
on May 12, 2001

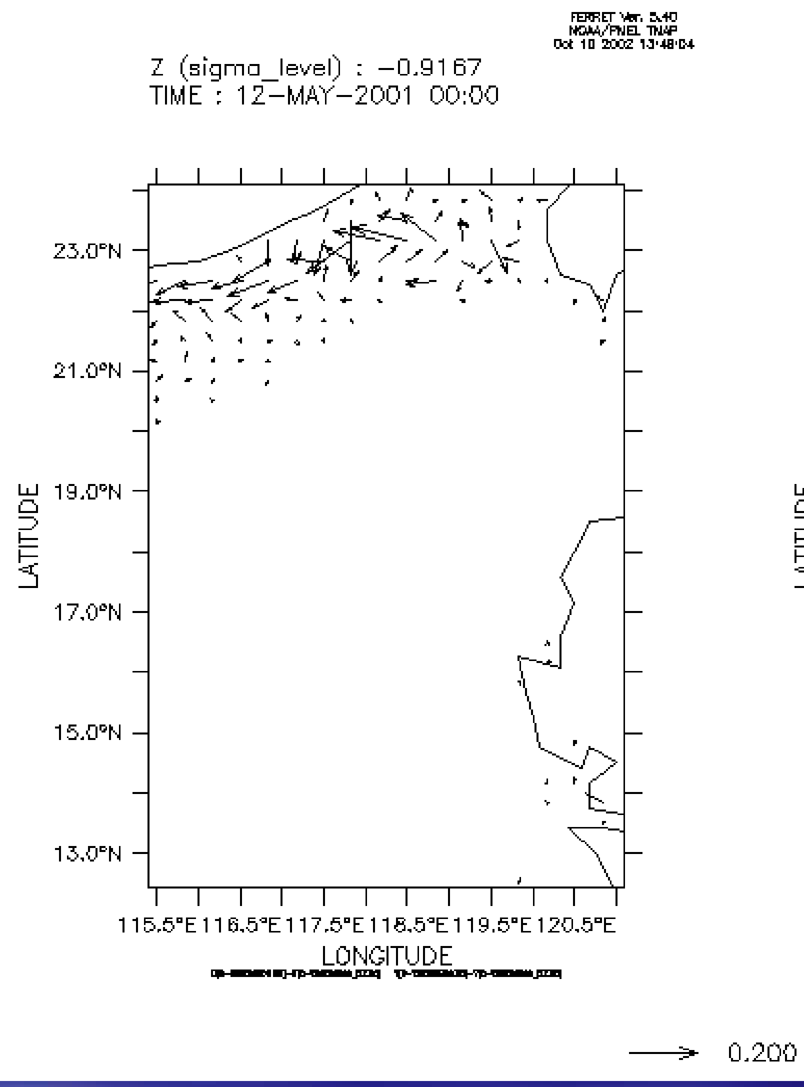


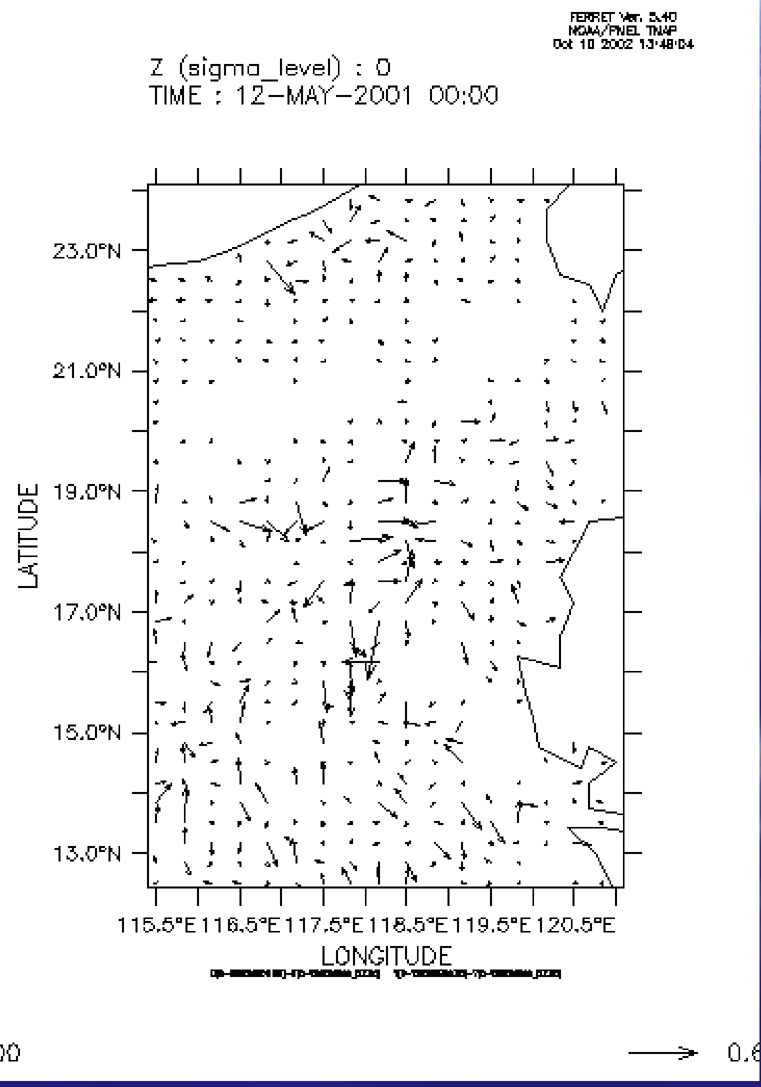
No surface & Yes Bottom wave effects





(No surface & Yes Bottom wave effects) - (No surface & No Bottom wave effects)





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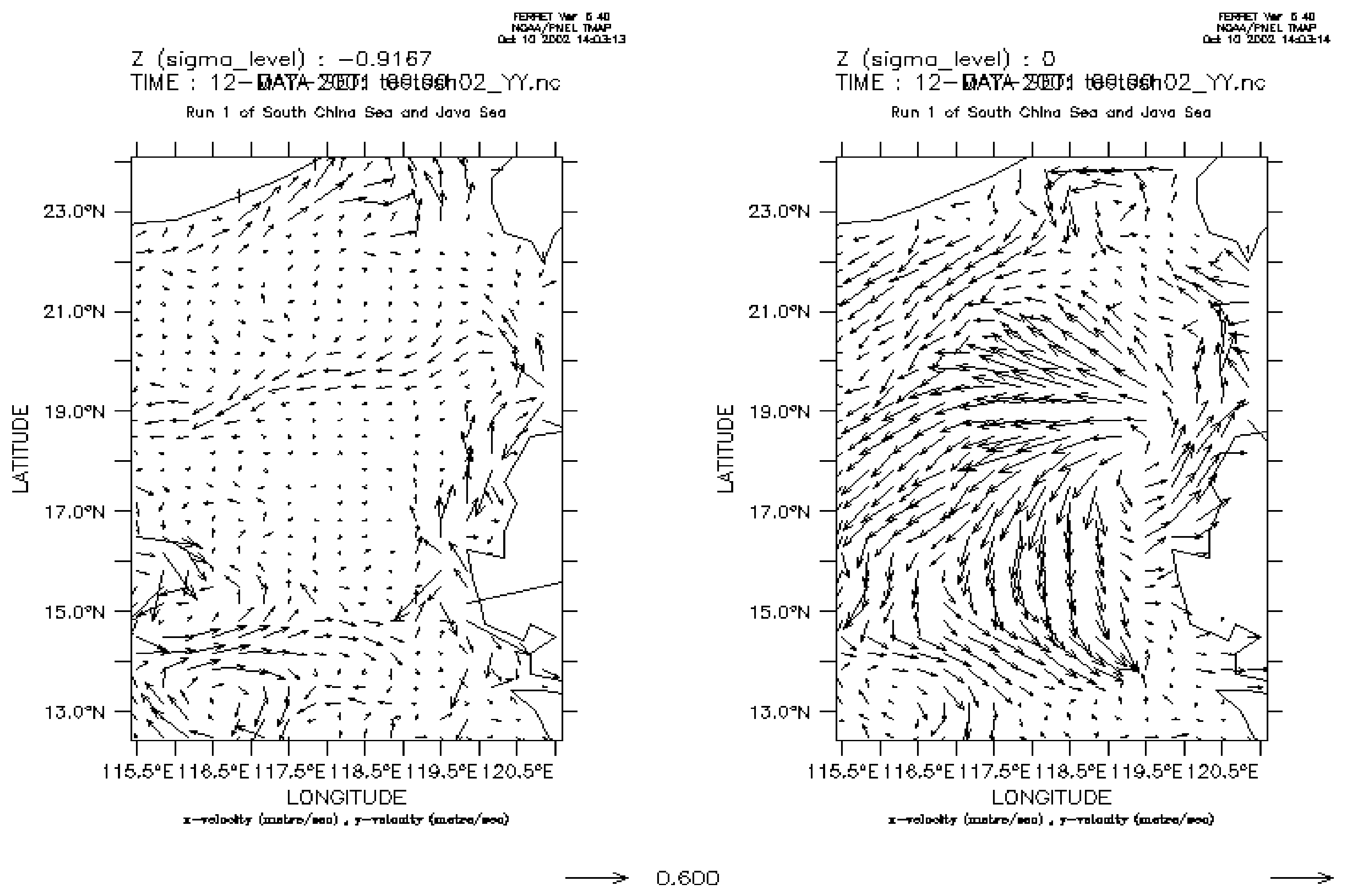

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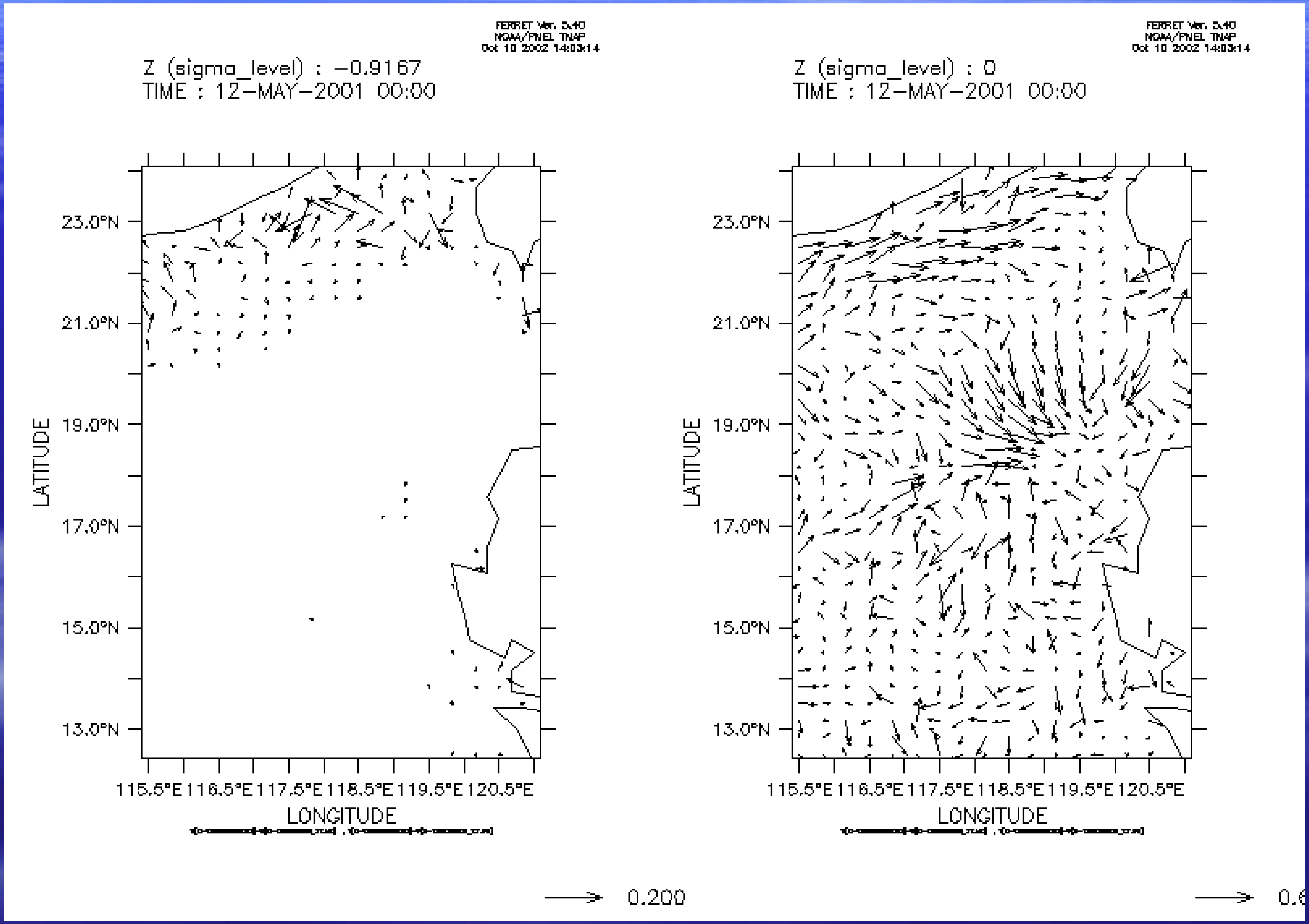

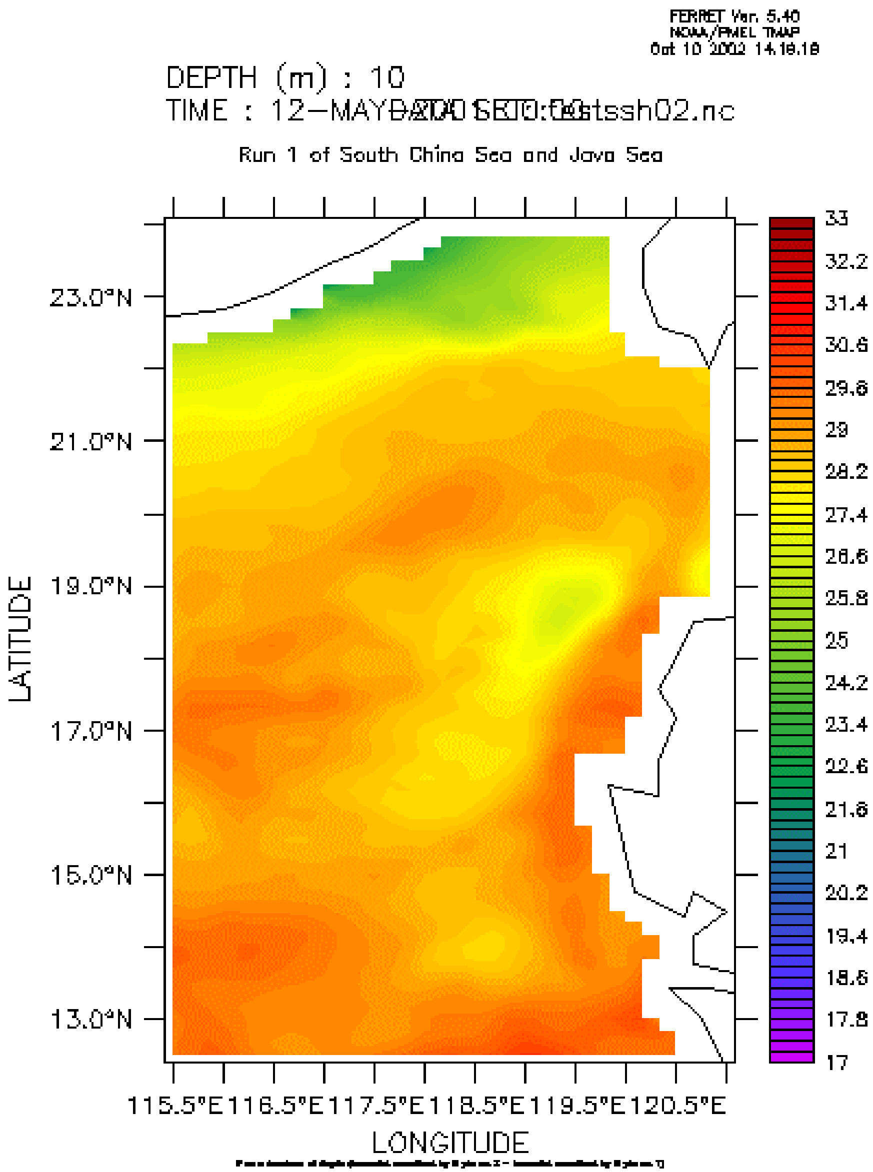
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Run 1 of South China Sea and Java Sea
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21.0°N
19.0°N
17.0°N
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115.5°E 116.5°E 117.5°E 118.5°E 119.5°E 120.5°E
LONGITUDE
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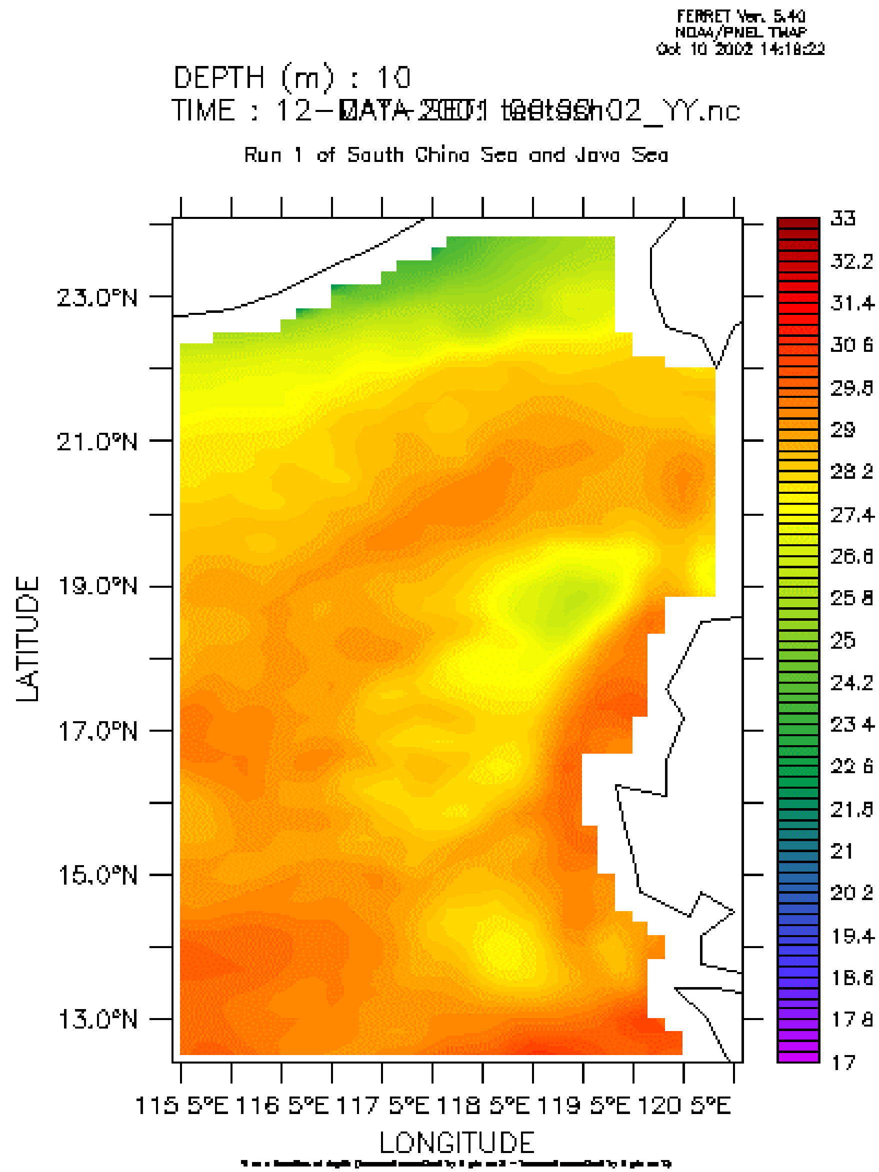
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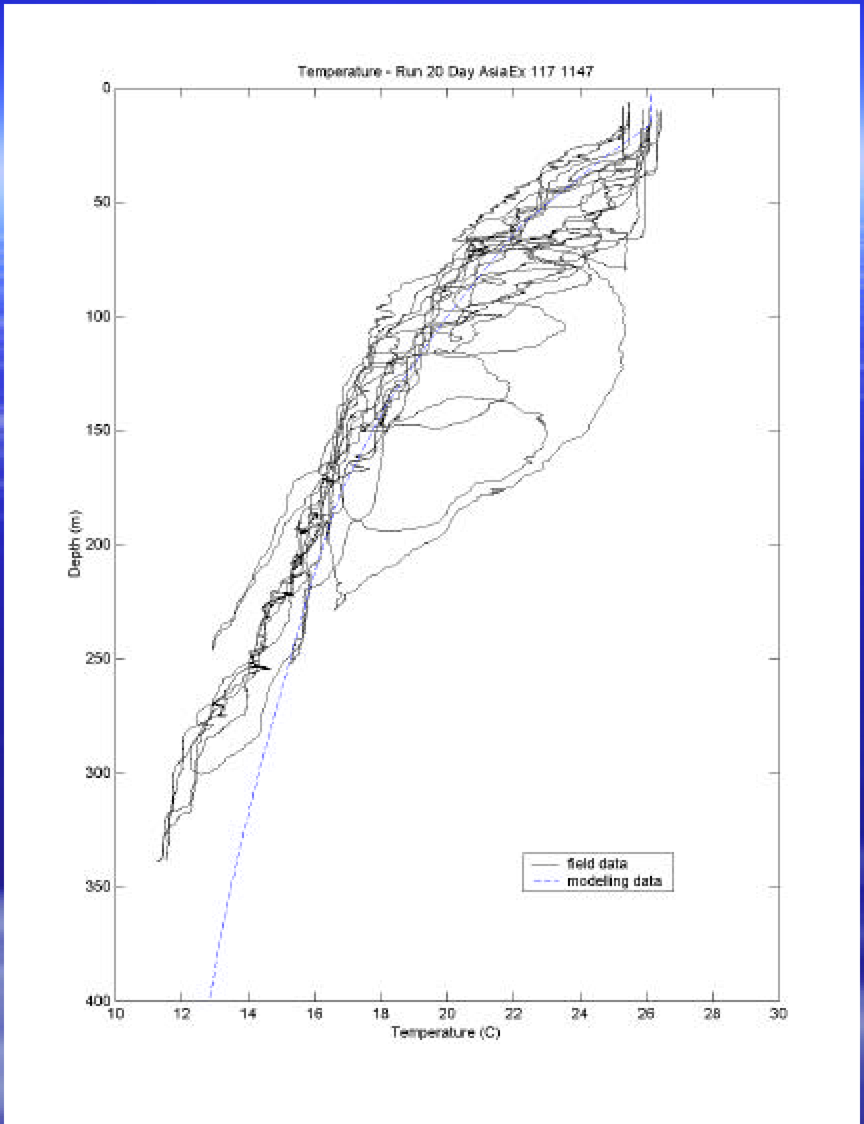
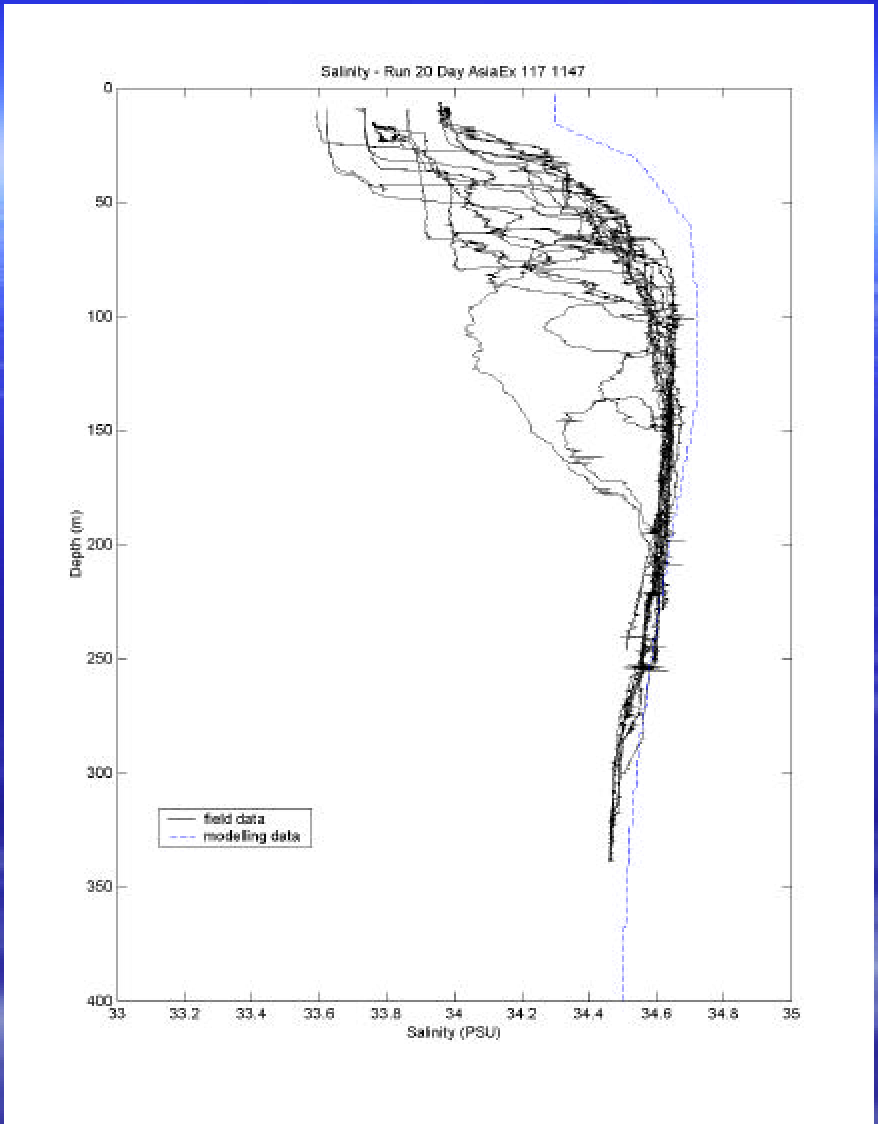
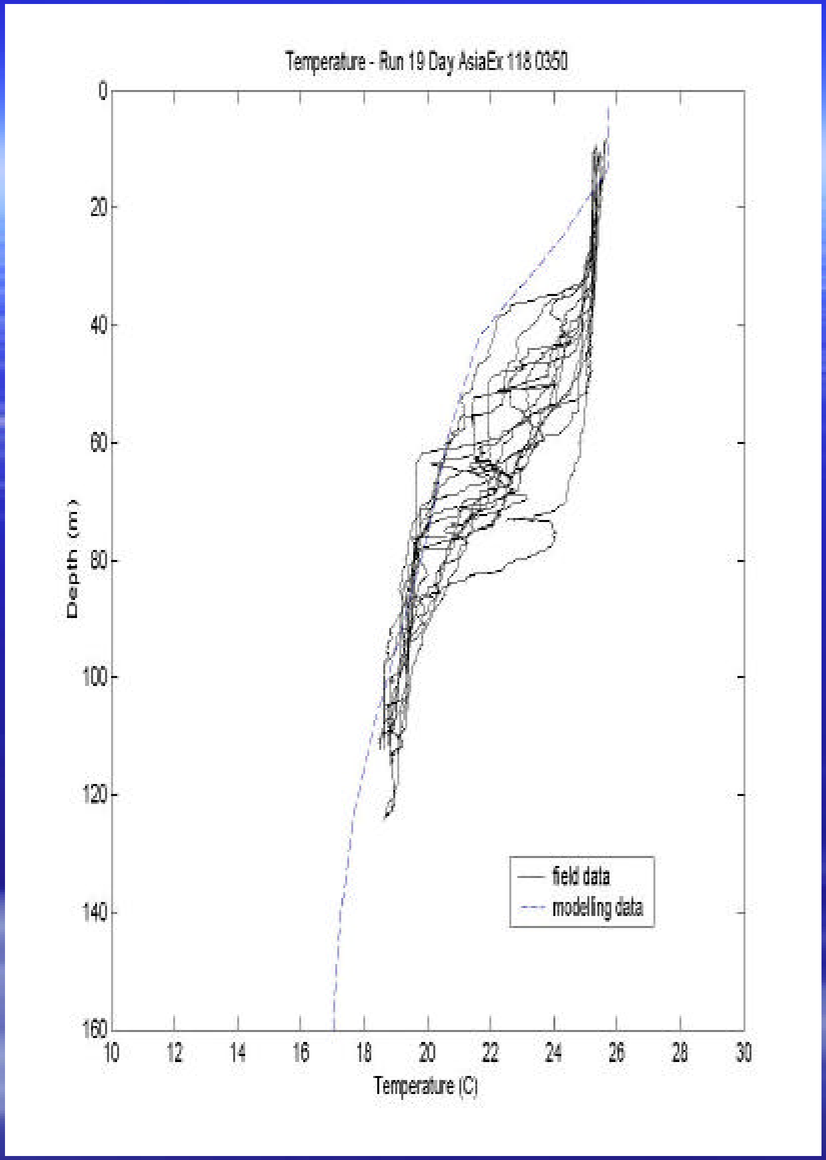
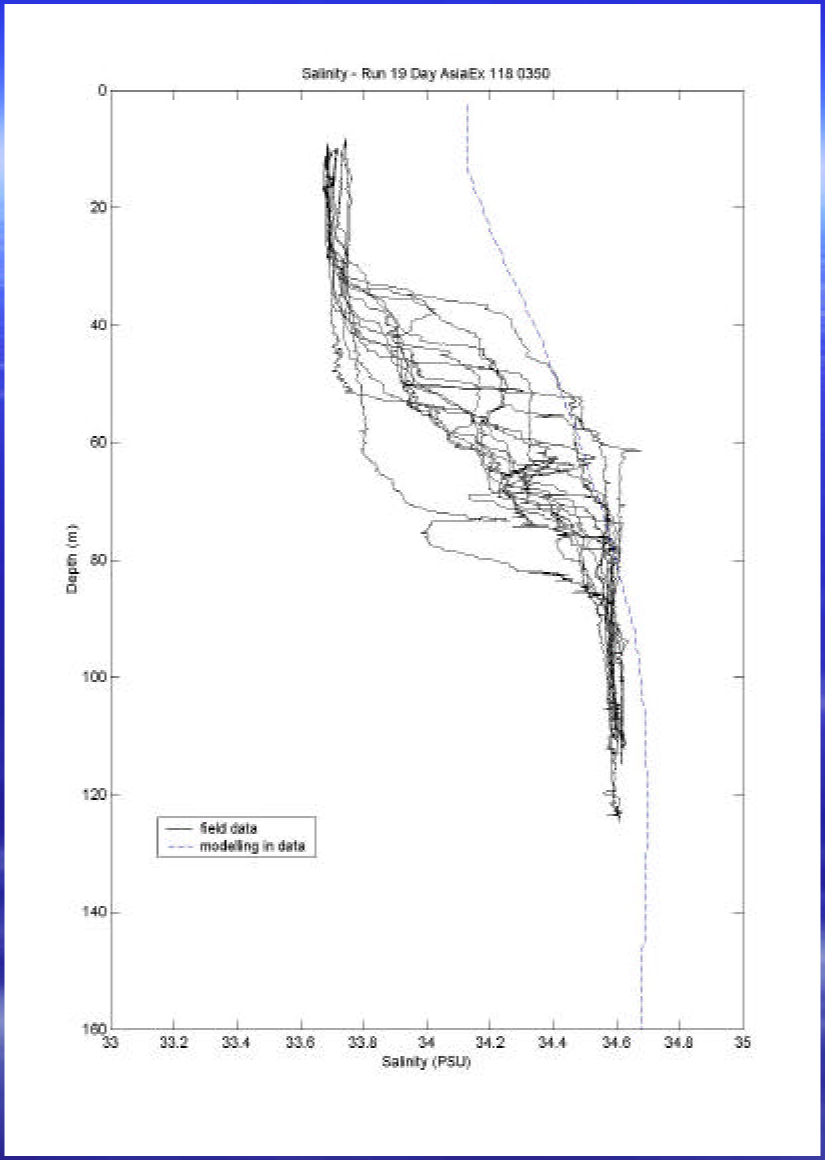




Measured vertical profile of temperature and salinity as compared with model output at point 21.6N, 117.7E.





Measured vertical profile of temperature and salinity as compared with model output at point 21.8N, 117.2E.

Data Assimilation

- **Local model:**

  Correction of model simulation with a forecast of the model error in measurement locations

- **Relaxation of Temperature and Salinity**
  - **SST**
  - **Climatologic data**
- **Kalman Filter:**

  Support the prediction of hindcasting, nowcasting and forecasting

Conclusions

- ✓A coupled ocean wave-circulation model has been implemented for the regional seas of South East Asia.
- ✓The influence of surface stress and bottom stress have been examined.
- ✓The coupled model would able to assist in the monitoring and assessing of the ocean environment in the region.